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Review

# Quantifying the energy, water and food nexus: A review of the latest developments based on life-cycle assessment

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ABSTRACT

Energy, water and food resource scarcity caused by rapid population growth, climate change, imbalanced ecosystems, and economic diversification, is the biggest challenge for today's world. In recent decades, the importance of the interdependent relationship between these resources has been recognized as the energy-water-food nexus. Sustainable resource consumption and the capability to ascertain true resource consumption is crucial for modern day development. As such, wide-spread adoption of the energy-water-food nexus methodology for integrated resource modeling can significantly contribute toward resource productivity and continuity. This methodology has expanded over the years, from concept development to application in multiple case studies. The methodology has also enabled the identification of synergies and trade-offs within the sub-systems that constitute the overall energy-water-food nexus system, hence providing a mechanism for optimization in resource consumption and minimization in the total environmental burden in the system under evaluation. This paper has reviewed the interlinkages inherent in the energy-water-food nexus, and the progress in developing suitable quantification methods. Although there is no standardized methodology for analysis involving the energy-water-food nexus, the life-cycle assessment methodology has been used as an enabler for the quantification of environmental burdens of systems evaluated using the 'Nexus' approach. As such, this paper will provide an overview of the different applications in which the life cycle assessment methodology has been applied to energy-water-food nexus analysis. The paper concludes that an integrated life cycle assessment and energy-water-food nexus methodology is necessary to determine environmental burdens for different scenarios presented within systems operating within an energy-water-food nexus environment, essentially influencing energy-water-food resource sectors.

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## 1. Introduction and background

Energy, water, and food (EWF) are the most basic elements for enabling human welfare and social security. Continuous pressure on these resources from a rapidly increasing population, coupled with ever increasing expectations from an affluent population for higher standards of living, presents a challenge for future generations. Crucial for a sustainable future in terms of global access to EWF resources and the need to prolong their availability is the need to manage them efficiently. Integrated resource management through modeling of the interrelationship between the three resources is necessary to simultaneously evaluate the impact on all of them as one resource sector is utilized. Considering climate change and other environmental burdens, the quantification of environmental impacts when EWF resource sectors are in operation is paramount to sustainable development. In this regard, the life-cycle assessment (LCA) methodology is important in determining the environmental loads of the delivery of a product and service utilizing EWF resource sectors across a range of impact categories.

### 1.1. Energy, water, and food sustainability

The growing demands for EWF are the result of rapid population and economic growth, unplanned urbanization, transformation in weather patterns, and, most importantly, the inefficient use of resources. Despite global efforts to achieve energy, water, and food security, approximately one billion people are considered undernourished, nearly 0.9 billion do not have sufficient access to safe water, and no less than 1.5 billion people are living outside the network of modern energy (Hoff, 2011). Because of the extra 60% and 80% global demand expected by 2050 for food and energy, respectively, water withdrawals are also projected to increase by 50% in just the next few years (Flammini et al., 2014). Policy implementation in one sector without considering the effects in other sectors can lead to a significant imbalance between these critical resources. Considering large water dams for example, they provide critical power generation and water for irrigation requirements. However, in some cases, they can seriously affect downstream food systems as a consequence. Similarly, production of biofuels ensures energy supply at the expense of huge water withdrawals and non-food production land use. The management of the interdependencies between EWF resources can enable informed decision making with respect to energy, water, and food supply and utilization.

Implementation and promotion of sustainability also addresses protection of the natural environment. Consumption of energy, water, and food within their respective sub-systems for social benefits often results in particular environmental burdens, which should be identified and mitigated where possible. Impacts on the environment include those related to greenhouse gas (GHG) emissions, eutrophication, acidification, human toxicity, and other environmental impacts. A holistic approach to integrate resource evaluation throughout their lifecycle coupled with an appreciation to the natural environment can overcome the challenge of future resource security, rather than a one-dimensional assessment of single resource sectors.

### 1.2. Historical overview of EWF nexus

Throughout the era of modern development, governmental bodies and research institutes have had their separate departments for setting policy related to the energy, water, and food sectors. In recent years, consideration for the interdependencies that exist between energy, water, and food in what is known as the “nexus” has received global recognition. Early in the 1970s, environmental experts noticed the significance of exploring the connections among energy, water, and food (Atlantic Council, 2011). In 1983, a food-energy nexus was introduced in the United Nations University, which received wider attention in the following year during the conference on “Food, Energy, and Ecosystems” in Brazil (Endo et al., 2017; Pretty, 1993). Connectivity between water and electricity (energy) was highlighted mainly in the western United States by the mid-1980s. Innovation of the “virtual water” concept, which is the water used to produce products or commodities, accelerated the concept of a water, food, and trade nexus (Allan, 2003). Interaction between water, energy, and food for a few selected countries was further discussed (Hellegers et al., 2008). Finally, at the Bonn 2011 conference organized by the German Federal Government in collaboration with International Food Policy Research Institute (IFPRI), the World Wildlife Fund (WWF) and the World Economic Forum (WEF), all participants shed full light on the importance of a nexus approach for achieving water, energy, and food security to support a green economy (Hoff, 2011). According to the Bonn 2011 conference report, the definitions of water, energy, and food security are:

- Water Security: Access to safe drinking water and sanitation;
- Energy Security: Access to clean, reliable, and affordable energy services for cooking and heating, lighting, communications, and productive uses; and
- Food Security: Availability and access to sufficient, safe, and nutritious food to meet the dietary needs and food preferences for an active and healthy life.

Highlighting the interrelationships between water, energy, and food systems, this nexus approach attempts to identify the mutual synergies and trade-offs between sectors (Al-Ansari et al., 2015). Optimizing resource utilization, thus fulfilling the demand for each sector, all whilst maintaining environmental and economic sustainability is the main goal of the energy-water-food (EWF) nexus approach.

### 1.3. Objective and review outline

Optimum consumption of resources, and the minimization of the environmental impacts in the delivery of different products and services is the key objective of the EWF nexus approach. As such, there is much emphasis on developing methodologies that

consider the identification of synergies and trade-offs between sectors to enable the realization of these objectives. The EWF Nexus approach is a holistic means towards integrated resource management, which emphasizes the interlinkages that exist between primary energy, water, and food resources. It provides opportunities to explore suitable solutions for the efficient use of resources within varying environments. Securing these resources for the future is equally as important as maintaining a sound environment.

To enable environmental assessment of product systems, LCA has been historically used in this regard. The LCA methodology enables the seamless connectivity between the EWF Nexus methodology and life cycle analysis of systems that deliver products and services. It identifies and quantifies system inputs and outputs and translates the latter into a range of environmental impact categories. The objectives of this review are to provide an overview of the interlinkages within the EWF nexus system and to highlight the importance of the integration of LCA tools in the quantification assessment of EWF Nexus case studies over the other existing nexus quantification tools. Inclusion of LCA provides a baseline against which policy makers can track performance and establish new techniques that enrich the total product or process system, thus reducing the overall environmental impacts. Being the most important of these topics, regional progress in EWF nexus research is also discussed in this review. Regions have been selected based on World Bank geographic region classification for the fiscal year 2016.

This review is organized under five major headings that describe: (1) water, energy, and food security; (2) the interlinkages between EWF resources (3) the development of regional nexus research; (4) nexus quantification methods and LCA use for nexus system analysis; and (5) conclusions and future scope.

## 2. Research methods

This study analyzes peer-reviewed journal papers published in English only covering several renowned databases (e.g. ACS publications, ScienceDirect, Taylor & Francis, Wiley) mostly from 2008 to 2017. Journal papers from other databases are also covered here (mentioned in Table 1) but fewer in numbers. The review mainly focuses on water, energy, and food sectors as well as their interrelationship. Nexus studies including water-energy-food-climate, water-land-energy are outside the scope of this review. As part of this review is based on the nexus research progress on different regions, peer-reviewed journals across the globe were considered. To improve the quality of the study, other sources such as academic theses and dissertations, public reports, technical journals, conference proceedings, book chapters and governmental documents were taken into consideration.

The search for the review papers was mainly conducted using specific keywords such as water-energy-food nexus, water-energy nexus, energy-water nexus, energy-food nexus, water-food nexus, regional WEF nexus study, and LCA in EWF nexus. The primary selected journal papers were gathered by searching these keywords in the journal title, keywords and in abstract content. The search for other documents such as academic and public reports was performed by searching the keywords in the headings or title only. The second phase of the search was based on elimination of duplicate papers, which resulted in 49 peer-reviewed journal papers and 30 other documents in total. All these selected papers and other documents were then grouped according to different categories for further review. Management of references was done using EndNote software from the beginning of the literature search. Table 1 provides a structure for the literature search into several selected categories and the final selected papers and other documents in different nexus areas are listed according to the aim of the review in Fig. 1.

## 3. Detailed analysis of the literature

This review reveals the connectedness among water, energy, and food systems through synergy and trade-off analysis. The following sections are the descriptive breakdown of each interconnection and the progress of nexus research in different regions worldwide.

### 3.1. Water, energy, and food linkages

Appreciation for the inextricable linkages amongst the water, energy, and food sectors are the primary foundation for ascertaining true resource consumption. The distinctive interlinkages among the water, energy, and food sectors are characterized in the following subsections.

#### 3.1.1. The water-energy nexus

The interdependent nature of water and energy can directly affect the availability and national security of both the water and energy sectors. This portion of the nexus is traditionally known as the water-energy nexus. It considers the water requirement for energy production (for extraction, transport, and processing of fossil fuels; power generation; and irrigation for producing biofuels) and the energy requirement for water abstraction, treatment, and supply (IEA, 2012). From the cause-effect relation, it is obvious that more energy is needed when demand for water quantity or quality increases and similarly more water is needed for increased energy production. For example, the hydroelectric turbines in Hoover Dam will cease to be function if water levels decline in Lake Mead, with a result of little or no power supply to Las Vegas. Conversely, a huge controversy existed over whether to establish

**Table 1**
Searching categories and keywords with database distribution.

| Categories | Database classification[a] | | | | | | Total articles[b] | Common/Mostly used keywords |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | | |
| Energy for water | 3 | 1 | 1 | – | 5 | 7 | 17 | Water use, energy intensity, energy use, energy intensity, water infrastructure, water-energy-food nexus, desalination |
| Water for energy | 3 | 2 | 1 | 1 | 2 | 6 | 15 | Water-energy nexus or interaction, water policy, energy, water, nexus |
| Water for food | 2 | 1 | – | 1 | – | 3 | 7 | Water footprint, water use |
| Energy for food | 2 | – | – | – | 1 | 3 | 6 | No common keyword |
| Regional EWF Nexus Study | 7 | 5 | – | – | 5 | 10 | 27 | Water-energy-food nexus, food security, policy integration, water security, emissions |
| LCA & EWF Nexus | 4 | – | 1 | 3 | 2 | 1 | 11 | Life-cycle assessment, food-water-energy nexus, water footprint, global warming potential |

[a] The classification of databases are as follows: A: ScienceDirect; B: Taylor & Francis; C: Wiley Online Library; D: ACS; E: other peer reviewed journal papers in different databases such as Springer Link (1), Nature (2), PubMed (1), ASCE (1), MDPI (6), IWA (1), IOP Science (2); F: other reports including governmental documents, public reports, academic thesis or reports etc.

[b] Total articles in all categories: 83; Duplicate: 4; Final analyzed article count: 79.

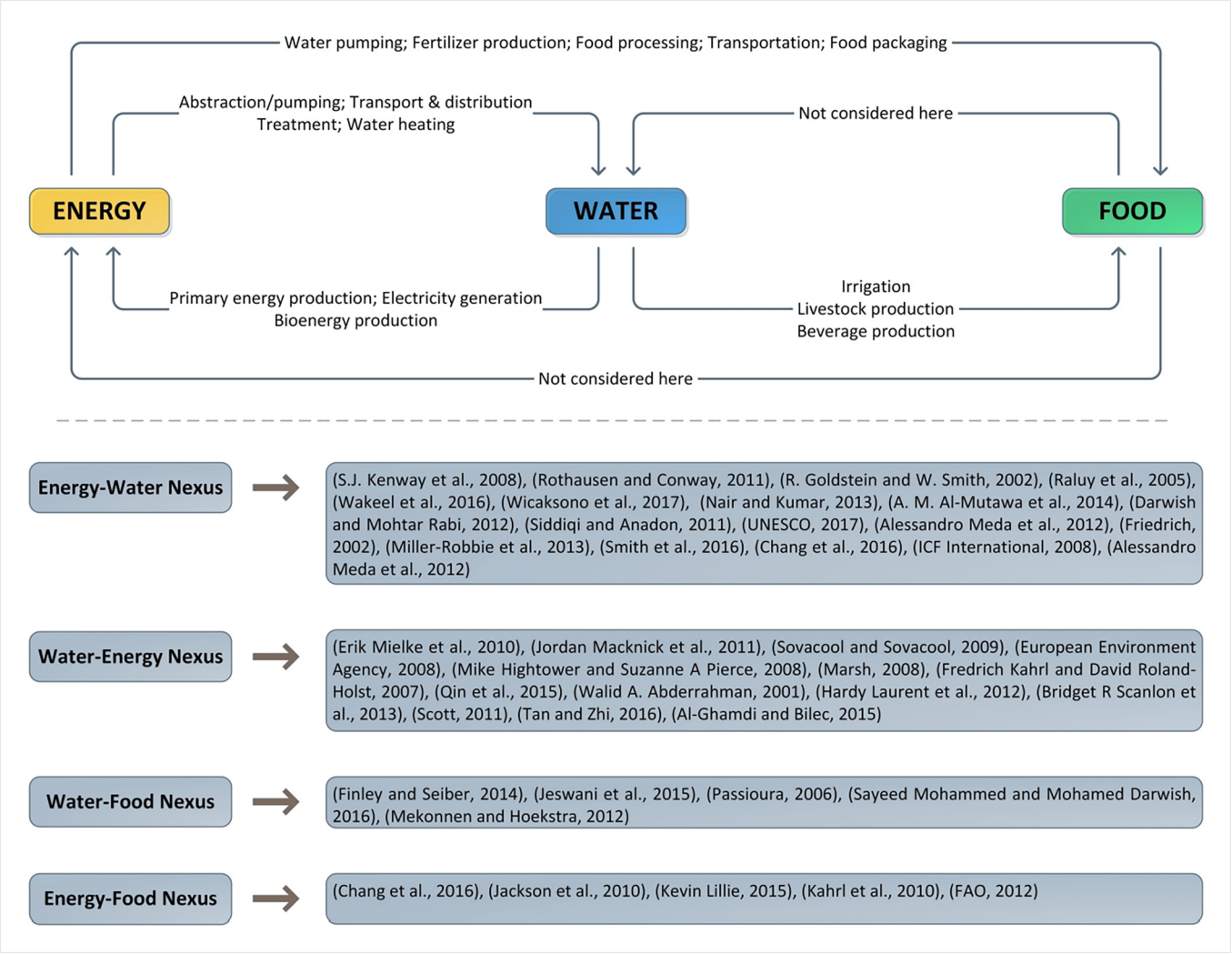
Water pumping; Fertilizer production; Food processing; Transportation; Food packaging
Abstraction/pumping; Transport & distribution
Treatment; Water heating
Not considered here
ENERGY
WATER
FOOD
Primary energy production; Electricity generation
Bioenergy production
Irrigation
Livestock production
Beverage production
Not considered here
Energy-Water Nexus
(S.J. Kenway et al., 2008), (Rothausen and Conway, 2011), (R. Goldstein and W. Smith, 2002), (Raluy et al., 2005), (Wakeel et al., 2016), (Wicaksono et al., 2017), (Nair and Kumar, 2013), (A. M. Al-Mutawa et al., 2014), (Darwish and Mohtar Rabi, 2012), (Siddiqi and Anadon, 2011), (UNESCO, 2017), (Alessandro Meda et al., 2012), (Friedrich, 2002), (Miller-Robbie et al., 2013), (Smith et al., 2016), (Chang et al., 2016), (ICF International, 2008), (Alessandro Meda et al., 2012)
Water-Energy Nexus
(Erik Mielke et al., 2010), (Jordan Macknick et al., 2011), (Sovacool and Sovacool, 2009), (European Environment Agency, 2008), (Mike Hightower and Suzanne A Pierce, 2008), (Marsh, 2008), (Fredrich Kahrl and David Roland-Holst, 2007), (Qin et al., 2015), (Walid A. Abderrahman, 2001), (Hardy Laurent et al., 2012), (Bridget R Scanlon et al., 2013), (Scott, 2011), (Tan and Zhi, 2016), (Al-Ghamdi and Bilec, 2015)
Water-Food Nexus
(Finley and Seiber, 2014), (Jeswani et al., 2015), (Passioura, 2006), (Sayeed Mohammed and Mohamed Darwish, 2016), (Mekonnen and Hoekstra, 2012)
Energy-Food Nexus
(Chang et al., 2016), (Jackson et al., 2010), (Kevin Lillie, 2015), (Kahrl et al., 2010), (FAO, 2012)

**Fig. 1.** Classification of reviewed nexus studies based on specific categories.

the USA's largest desalination plant or not to fulfil the water demand of San Diego, due to local power supply shortage (Webber, 2008). Identification and understanding of the water-energy nexus can help solve the dilemma between energy production and water facilities. Establishment of energy production plants and water facilities requires an integrated approach exploring the interdependency of these critical resources in identifying stress points and in maintaining the balanced distribution between them depending on demands.

### 3.1.2. Energy for water

One segment of the water-energy nexus connects the requirement of energy for different water use cycles: abstraction (e.g., pumping from groundwater or surface water), transport and distribution (e.g., supply of water through pipelines), treatment (e.g., desalination), household use (e.g., heating water), and wastewater treatment (e.g., treatment for reuse). The amount of energy used for different activities related to water facilities depends on several factors such as distance, topography, climate, temperature, water volume, pipeline length and diameter, water quality and even technology used (Kenway et al., 2008; Wakeel et al., 2016; Wicaksono et al., 2017). Electricity is the main form of energy used in water use cycles, and, generally, the unit of electricity consumption is known as energy intensity.

Typically, energy is required for abstraction of water from groundwater aquifers, rivers, oceans, lakes, and manmade or natural reservoirs. Based on its many advantages, groundwater is used as a main source of water supply for many countries worldwide. Theoretical research has established that the amount of energy required to lift 1 $m^3$ of water up 1 m is approximately 0.0027 kWh (Rothausen and Conway, 2011), thus utilizing surface water supply requires 20–30% less direct energy after all conveyance, treatment and distribution energy expenditure than groundwater supplies (EPA, 2013; ICF Consulting, 2002). Treatment of raw water is a process that is highly energy intensive, with the energy requisite depending on factors such as contamination level, final water quality, technology applied, and location. For example, water treatment, supply and wastewater collection and treatment for the public and private entities in the USA consumes around 4% of total energy production there (Copeland and Carter, 2017; ICF Consulting, 2002). Energy use is more severe for non-conventional water treatment such as desalination (Raluy et al., 2005a, b; Wakeel et al., 2016; Wicaksono et al., 2017). Some countries, such as those in the Middle East with very limited natural water resources, are dependent on desalination for the majority of their water supply (Darwish and Rabi, 2012). Several

desalination processes are used globally, including reverse osmosis (RO), multistage flash distillation (MSF), multiple effect distillation (MED), electro dialysis (ED), and mechanical vapor compression (MVC). Energy requirements in these processes vary depending on the technology used, water volume, quality of end product, and efficiency of the process. MSF, MED, and MVC distillation are operated as thermal processes that consume mainly heat as the form of energy. RO and ED technologies are membrane based, which require electricity to purify water. Around 60% of global desalination processes use RO technology for its low energy consumption nature but MSF and MED continue to dominate in the Middle East (Nair and Kumar, 2013). From a nexus perspective, the combined consideration of power generation and water is necessary. For example, when excess heat is available, through fossil fuel and geothermal technologies for instance, the impacts of thermal desalination techniques become much less significant. Similarly, when abundant renewable energy sources are available, the impacts of desalination methods are significantly reduced (Raluy et al., 2005a, b). Table 2 summarizes different desalination technologies and their energy consumption values.

Treated raw water supply for use in the commercial, industrial, and public sectors consumes significant energy. Depending on distance and water demand, the energy requirement varies from place to place, but according to a range of values reported from research, it can be predicted that most Asian countries use less energy than European countries in regards to water supply (Wakeel et al., 2016). For example, India and China use 0.3 and 0.29 kWh/$m^3$ energy, respectively, for urban water supply, whereas Germany and Toronto use 1.71 and 0.68 kWh/$m^3$ energy accordingly (Friedrich, 2002; Meda et al., 2012; Miller et al., 2013; Smith et al., 2016). Such differences may be associated with age of the infrastructure which tends to be older in Europe and North America and due to higher population densities and city sizes in South and East Asian cities resulting in reduced network distances and larger pipe diameters per capita. Additionally, the end use of water tends to be more energy intensive, and the energy is consumed for activities such as water heating. Conservation of water at domestic and industrial levels can be proven as the most effective option for energy saving in the water sector; such initiatives are the basis for green building rating systems e.g., Leadership in Energy and Environmental Design (LEED) (Chang et al., 2016).

Collection of wastewater from a source such as a household and redistribution of treated wastewater requires high energy use and, according to the treatment level (primary, secondary, or tertiary), different amounts of energy are used in the operation phase. Primary factors that decide the energy need are quality of inflow and outflow (Wicaksono et al., 2017). The energy diversity for different levels of treatment in Australia is 0.01–0.37 kWh/$m^3$, 0.305 kWh/$m^3$, and 0.40–0.50 kWh/$m^3$ for primary, secondary, and tertiary treatments, respectively (ICF International, 2008; Radcliffe, 2004).

Energy intensity in different water use cycles for selected countries is presented in Fig. 2. It can be seen that the most significant contributors to total urban water cycle use is associated with residential end use, raw water treatment and water supply & conveyance. For raw water treatment the most significant difference lies in whether desalination is utilized or not. Energy requirement in residential water use has the variation as sometimes the energy use data has been listed in literature only for hot water system while other literature reported the energy data for hot water and other water activities in residential sector e.g. washing machine, dishwasher, swimming pool, etc.

### 3.1.3. Water for energy

Water use in energy production mainly falls into two categories: water use for primary energy production (Mielke et al., 2010) and water use for electricity generation (Macknick et al., 2011; Sovacool and Sovacool, 2009). In both cases, the procedures vary according to different technologies and so does the water requirement. After the agriculture sector, the energy sector is considered the second largest user of water (EEA, 2008; Hightower and Pierce, 2008). Identification of the water requirement in the energy sector has improved in recent years owing to the water crisis in some water-stressed regions, e.g., Australia (Marsh, 2008), China (Kahrl and Roland-Holst, 2007; Qin et al., 2015), the Middle East and North African (MENA) region (Abderrahman, 2001), Spain (Hardy et al., 2012), the United States (Scanlon et al., 2013), and Mexico (Scott, 2011). Research focusing on water use in energy mainly includes different energy types such as coal, oil, gas, nuclear, solar, geothermal, wind power and biomass production (Tan and Zhi, 2016). Analysis of water depletion owing to building energy use concluded that the amount of water depletion varies with the change in primary energy sources (Al-Ghamdi and Bilec, 2015). The consumed water volume to produce a unit amount of energy is known as water intensity, and generally the unit is $m^3$/MWh. The global average water consumption for fuel extraction and refining, and electricity generation is presented in Fig. 3.

Abundant water supply has always been considered a critical issue in electric power generation, as it requires considerable

**Table 2**
Energy requirements for desalination processes.

| Technique | Electrical Energy Consumption (kWh/$m^3$) | Thermal Energy Consumption (MJ/$m^3$) | Dominating Countries | References |
|---|---|---|---|---|
| Reverse Osmosis (RO) | 2.5–7 | None | USA, Spain, Trinidad, Cyprus, Singapore, KSA, Oman, UAE, Israel, Australia | (A. M. Al-Mutawa et al., 2014; Darwish, 2014; National Research Council, 2008; Siddiqi and Anadon, 2011; Wakeel et al., 2016) |
| Multi Stage Flash (MSF) | 3–6 | 190 (GOR[a] = 12.2) –390 (GOR = 6) | UAE, Qatar, Kuwait, KSA | (A. M. Al-Mutawa et al., 2014; Darwish, 2014; National Research Council, 2008; Siddiqi and Anadon, 2011; UNESCO, 2017; Wakeel et al., 2016) |
| Multiple Effect Distillation (MED) | 1.5–2.5 | 230 (GOR = 10) - 390 (GOR = 6) | UAE, Iran | (A. M. Al-Mutawa et al., 2014; Siddiqi and Anadon, 2011; UNESCO, 2017) |
| Electro Dialysis (ED) | 0.5–1.7 | None | Israel, Italy | (National Research Council, 2008; Wakeel et al., 2016) |
| Mechanical Vapor compression (MVC) | 7.9–15.85 | None | Bahrain, Italy | (A. M. Al-Mutawa et al., 2014; National Research Council, 2008; Wakeel et al., 2016) |

[a] Gained output ratio (GOR) can be described as the amount (kg) of produced distillate per kilogram of steam consumed and typically higher GOR systems cost more but consume less operating energy.

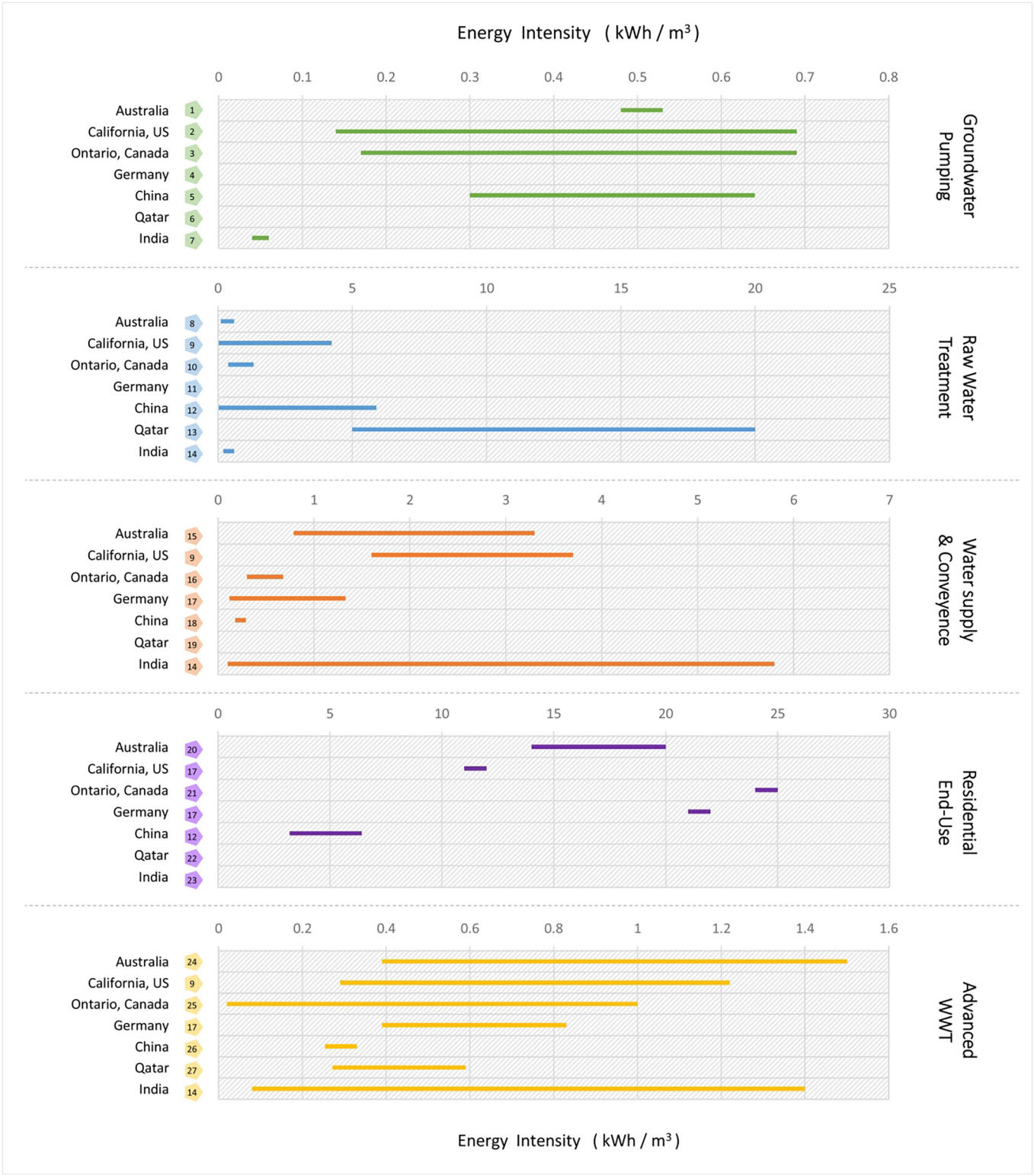


**Fig. 2.** The range of energy intensity in different water use cycle for selected countries. The numbers in the pentagon shape refer to the references. The energy intensity data for different water use cycle were collected for different countries from the following references: 1: (Rocheta and Peirson, 2011), 2: (Klein, 2005), 3: (Maharjan, 2015), 4: N/A 5: (Wang et al., 2012), 6: NA, 7: (Shah, 2009), 8: (Marsh, 2008), 9: (Klein, 2005; Meda et al., 2012), 10: (Carol Maas, 2010; Wakeel et al., 2016), 11: N/A, 12: (Hu et al., 2013), 13: (Darwish and Rabi, 2012), 14: (Miller et al., 2013), 15: (Kenway et al., 2008), 16: (Friedrich, 2002; Maharjan, 2015), 17: (Meda et al., 2012), 18: (Smith et al., 2016), 19: N/A, 20: (Apostolidis, 2010; Kenway et al., 2008), 21: (Carol Maas, 2010), 22: N/A, 23: N/A, 24: (Kenway et al., 2008; Plappally and Lienhard V, 2012), 25: (Maas, 2009), 26: (Plappally and Lienhard V, 2012; Xie and Chengwen, 2012): and 27: (Siddiqi and Anadon, 2011). The different panels are not on the same scale.

amounts of water for cooling and scrubbing purposes. The selection of once-through or recirculating cooling (where dry cooling is not possible) need to consider the associated impacts of water withdrawals (larger for once-through but mostly returned to the environment) and water consumption (larger for recirculating and lost from the local environment through evapotranspiration). For pollution control of sulfur, mercury, and other particulates in thermoelectric power plants a large quantity of water is required for scrubbing (Union of Concerned Scientists, 2017). Therefore, drought and other water stress conditions in different parts of the world have the potential to shut down power generation units. Incidentally, biofuels, which have been promoted for reducing certain negative environmental impacts, consume more water than conventional energy generation. The projected water consumption related to worldwide traditional biomass production for 2020–2050 in various countries is presented in Table 3. Other important uses of water related to energy generation include transportation of coal through slurries and checking for leakage in energy pipelines (DOE, 2006).

### 3.2. The water-food nexus

An increase from 3100 to 4500 billion $m^3$ of global water withdrawal is projected in the next 13 years (by 2030) in the agricultural sector, which is currently responsible for around 70% of global water consumption (FAO, 2014). As a region of focus, Asia is known as the highest user of water for agriculture while in other sectors, e.g. for industrial use, Asia, North America and Europe utilize almost the same amount of this resource (Finley and Seiber, 2014). Insufficient water supply tends to lower down the value addition in the agricultural production. For example, use of fertilizer by African farmers in sub-Sahara region is limited to 9 kg fertilizer in each hector where it reaches to 100 and 130 kg/hectare in case of South and East Asia respectively (Ozturk, 2017). Increased production of quality foods for the growing population requires more irrigation. Changing lifestyles have led to variation in meals, which has also influenced the water requirements of agriculture. Nearly 40% of the consumed food globally is produced in artificially irrigated lands (Foundation on Future Farming, 2008). Table 4 presents the irrigation water requirements in different parts of the world. The use of water in fertilizer manufacturing processes is also considered an indirect consumption in the water-food nexus.

In developed and developing countries, cereals are one of the most consumed food products. Production of 1 kg of different types of cereal products consumes around 1.75 L water in Bremen, Germany; 1.52 L in Valls, Spain; 4.83 L in Manchester, UK; and 1.25 L in Wexham, UK. The differences in water consumption are due to the different manufacturing processes and the type of cereal, e.g., flaked, puffed, shredded, and granola type cereals (Jeswani et al., 2015). The use of water for agriculture in different countries varies according to climate, crop type, soil characteristics, water quality, availability, and cultivation techniques.

Reallocation of food crop production throughout the world in an organized way can reduce the amount of water required for irrigation. According to water productivity (crop yield per cubic meter of water consumption), water-intensive crop production can be shifted to the areas with highest water productivity (Passioura, 2006), or areas of high water availability. For instance, from Table 4 it can be seen that the water efficiency is low in the Middle East countries due to high rates of evapotranspiration, while water

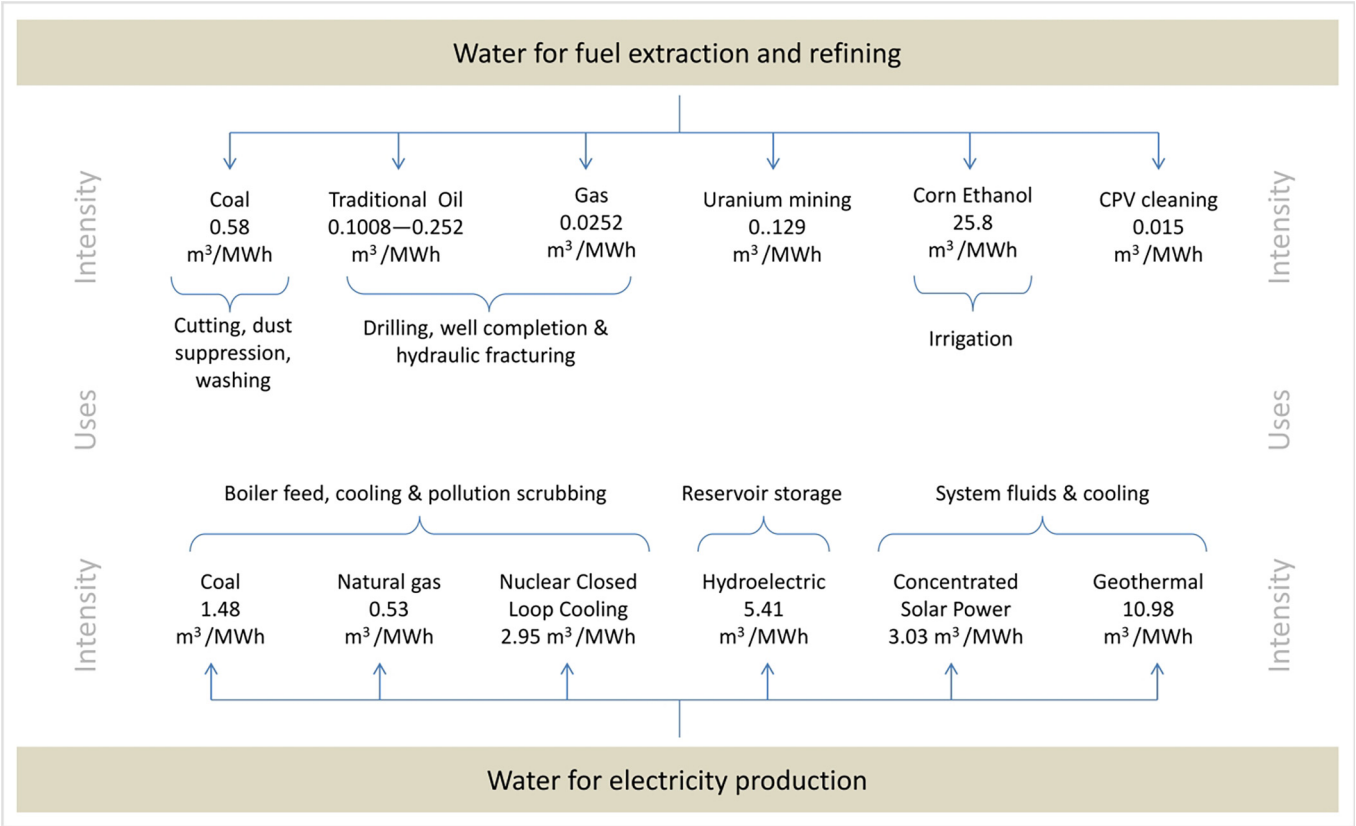


**Fig. 3.** Water consumption for energy production based on US average condition. Water is used mainly in resource extraction and refining for primary fuel production and also used in electricity generation purpose (IEA, 2012).

**Table 3**
Projected water consumption related to traditional biomass production. Data was extracted from (UNESCO-IHE Institute for Water Education, 2008; World Energy Council, 2010).

| Year | Africa | | Asia | | Europe | | North America | |
|---|---|---|---|---|---|---|---|---|
| | PP (EJ) | WC (Bill. $m^3$) | PP (EJ) | WC (Bill. $m^3$) | PP (EJ) | WC (Bill. $m^3$) | PP (EJ) | WC (Bill. $m^3$) |
| 2020 | 10.5 | 745.6 | 22.5 | 805.6 | 1.8 | 22 | 0.7 | 20.4 |
| 2035 | 11.3 | 802.4 | 21 | 749.7 | 1.8 | 22.3 | 0.7 | 19.3 |
| 2050 | 10.4 | 744.2 | 19.3 | 690.2 | 1.9 | 22.9 | 0.6 | 18.4 |

PP = Primary Production.
WC = Water Consumption.

**Table 4**
Amount of renewable freshwater resources and water in irrigation by countries (Frenken and Gillet, 2012; Nabil Dabour, 2006).

| Country | Total renewable freshwater resources ($km^3$/year) | Irrigation water requirement ($km^3$/year) | Irrigation water withdrawal ($km^3$/year) | % irrigation water withdrawal | % water efficiency[a] |
|---|---|---|---|---|---|
| Australia | 492 | 3.892 | 6.596 | 1.1 | 59.0 |
| China | 2840 | 256.9 | 358 | 12.6 | 71.8 |
| Mexico | 457.2 | 26.03 | 58.78 | 12.9 | 44.3 |
| Spain | 111.5 | 14.06 | 19.56 | 17.5 | 71.9 |
| Qatar | 0.058 | 0.076 | 0.262 | 452 | 29.0 |
| KSA | 2.40 | 11.6 | 20.83 | 870 | 55.7 |
| USA | 3069 | 108.5 | 177.4 | 5.8 | 61.2 |

[a] Ratio of water required vs withdrawn for irrigation.

**Table 5**
Global average water footprint and virtual water per country for specific crop. Crops with a high yield have a smaller water footprint than crops having low yield (Mekonnen and Hoekstra, 2010). Difference in virtual water used in different primary crops is mainly due to the climate, applied technology etc. (Lenntech, 2017).

| Crop | Global Water footprint ($m^3$/ton) | Global yield (ton/ha) | Virtual water per food per country ($m^3$/ton) | | | | |
|---|---|---|---|---|---|---|---|
| | | | USA | China | India | Mexico | Australia |
| Cotton | 4029 | 1.73 | 2535 | 1419 | 8264 | 2127 | 1887 |
| Rice | 1673 | 3.90 | 1903 | 1972 | 4254 | 3257 | 1525 |
| Soybean | 2145 | 2.24 | 1869 | 2617 | 4124 | 3177 | 2106 |
| Sugarcane | 210 | 64.96 | 103 | 117 | 159 | 171 | 141 |
| Wheat | 1827 | 2.74 | 849 | 690 | 1654 | 1066 | 1588 |

is also extremely limited for the same reason.

Reallocation of food production requires the international trading of food crops and associated virtual water (the water used to produce raw foodstuffs) (Table 5). Importing the water-intensive food crops and other foodstuffs thus saves large volumes of irrigation water for the importing country. Water-scarce regions such as the Middle East and Mexico are considered the biggest importers of virtual water, which allows countries in these regions to save more of their domestic water resources. For example, Qatar has an average virtual water trade of 1360 $Mm^3\ y^{-1}$ and increased agriculturally oriented virtual water trading up to 90% in 2015 by importing 1662 kilotons of food (Mohammed and Darwish, 2016). This process secured the food supply and saved the renewable water resources in Qatar, which as apparent in Table 4, are under significant pressure from existing agriculture.

Along with cultivated crops, animal production for meeting human needs also requires large amounts of water. For an equivalent nutritional value, the water footprint (WF) for beef is 10 L/kcal but only 0.5 L/kcal for cereals and starchy roots (Mekonnen and Hoekstra, 2012). Similarly, production of beverages also consumes significant amounts of water.

### 3.2.1. The energy-food nexus

The energy-based mechanism for increased food production was introduced via the "green revolution" in the agricultural sector. Approximately 30% of global available energy is invested in the agricultural food chain (FAO, 2012). The use of fossil resources for machinery and electricity for pumping water is considered direct consumption of energy for food, whereas energy use for producing fertilizers is considered indirect use (Chang et al., 2016; Jackson et al., 2010). In detail, the steps along the agricultural food chain are production of crops, fish, livestock, and forestry products; postharvest operations; food storage and processing; food transport and distribution; and food preparation (FAO, 2012). In the USA, the total energy use for producing food is divided into four main groups: 21% for crop cultivation, 14% for transportation, 11–16% for food processing, and around 50% for food handling (e.g., food packaging, service, and sales) (Lillie, 2015). Energy inputs for producing the UK's nine main crops are listed in Fig. 4.

Half of the energy used for nonorganic bread wheat production

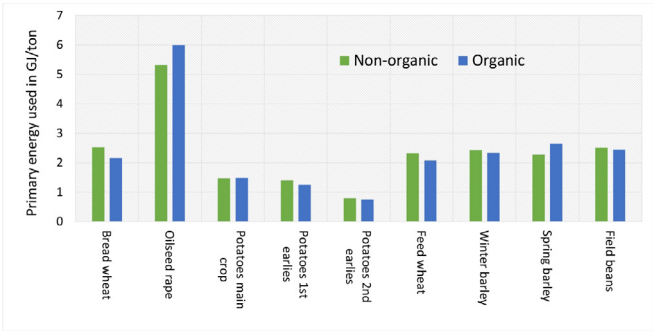


**Fig. 4.** Energy inputs in arable crop production (Williams et al., 2006; Woods et al., 2010).

in the UK goes to nitrogen-based fertilizer production, whereas the organic version uses more diesel per unit of production due to the lower yields. For potatoes, their long storage time leads to higher energy consumption than other crops. Production methods of fertilizers are also responsible for consumption of different amounts of energy. In most of the European countries, natural gas is used for fertilizer production, but, in China, nitrogen-based fertilizers are being produced using energy from coal (Kahrl et al., 2010). Identification of energy and food production relationships can improve the energy use efficiency of the agricultural sector, along with effective food production.

### 3.3. Regional progress in nexus research

The EWF nexus has gained priority globally in different sectors, e.g., in scientific research and policy making in industries for sustainable environment settlements (Ozturk, 2015). By addressing the critical dimensions and challenges in each specific sector (water/energy/food) and their interlinkages, nexus study has appeared as a development parameter for society in many areas of the world. Many nexus studies have been conducted for specific regions in the last few years, and several countries have implemented this nexus concept in development practices. Nexus research development and implementation practices in different parts of the world are listed in Table 6. Selection of regions was based on the World Bank geographic region classification for the 2016 fiscal year (The World Bank, 2016).

According to the World Bank regional classification, countries such as Afghanistan, Pakistan, India, Sri Lanka, and Bangladesh are included in the South Asia zone. The selected studies herein present Sri Lanka, the Hindu Kush Himalayan region, Bangladesh, and India, which show general growing trends in the EWF nexus study for securing water, energy, and food resources but still lack implementation of the nexus in the policy sector. The Africa region as per the World Bank classification comprises 48 countries. Most of the recently published research for the Africa region focused mainly on South Africa where water is distributed very unevenly. The research highlighted the water-energy policy recommendations, influence of water and energy in food pricing, and impact on water availability due to climate change.

In the Europe and Central Asia regions, solving joint challenges within the EWF sector has been the goal, for which some researchers have implemented additional features such as hydropower generation and changes in irrigation patterns. Other researchers have focused on the impacts of energy and food production on river systems. EWF security studies for Latin America and the Caribbean zone addressed the environmental degradation; thus, nexus research has emerged there as a sustainable solution for governing these natural resources. Despite the sub-regional differences in the Middle East and North Africa (MENA) region, all countries are struggling to cope with their water shortages and are concurrently trying to be self-sufficient to fulfil food security aspirations. These countries strongly depend on their fossil fuels to produce energy and are trying to explore opportunities in the renewable energy sector. Understanding the interrelations between the water-energy-food sectors is critical here for developing an integrated system for resource management. Studies performed in this region conveyed the message of strong focus on the EWF nexus for better policies and solutions for meeting the dynamic challenges.

The East Asia and Pacific region is made up of countries such as China, those of the Pacific Islands, and Vietnam. The extreme drought conditions in Australia have stretched the necessity of water resource management across the energy, agriculture, and water sectors; thereby, EWF nexus research is playing a key role in Australia by providing the best strategies for resource management along with economic evaluation. Nexus study has become the center of attention in China, as the demands for energy and water are growing very rapidly with the increasing population and economic growth. China accommodates 22% of the world's population, but owing to geographical conditions, possesses only 6% of its freshwater resources (2300 $m^3$ per capita), which are distributed unevenly (Guan and Hubacek, 2008). Electricity production (dominated by coal) grew threefold in just ten years, from 2000 to 2010, and is now considered the second highest consumer of water. Nearly 95% of China's coal mines are underground, which require more water, yet the availability of this resource is limited in coal-rich areas. These critical issues make the water-energy nexus particularly important for China.

## 4. Development in nexus quantification method

The goal of understanding EWF interlinkages, and ultimately system assessment using a nexus approach, is to encourage more environmentally and economic alternatives, together with informed policy making to create a more sustainable society. Transformations in society due to the continuous pressure on natural resources and associated environmental impacts reveal the need for sustainable resource management, and the EWF nexus approach is one way to do so. The EWF nexus approach seeks to ascertain resource consumption through the identification of interlinkages that exist between the three components (Al-Ansari et al., 2015). The EWF nexus approach also encourages the establishment of policies that are more integrated in terms of these resources.

Quantitative assessment of the EWF nexus is particularly important to provide indications on the performance of the system in question. The aim of nexus quantification is to provide more refined and detailed assessments of specific EWF nexus interlinkages via simulation, occasionally allowing environmental impacts to be scored. The aim of using LCA tools in an EWF nexus study is to draw different environmental impact scenarios to implement sustainable use of water-energy-food resources, thus reducing negative effects on the environment. The collection of nexus tools available for assessment is discussed in the following sections with specific focus on the role of LCA.

### 4.1. Analysis of the existing nexus quantification framework

Assessment of the water-energy-food nexus requires an analytical framework, including a robust model, reasonable algorithms, and a complete dataset. Table 7 below highlights some of the existing tools that have contributed toward the development of the EWF nexus methodology.

### 4.2. Life cycle assessment tool in nexus study

Uncertainty and failures in resource management, especially in the water, energy, and food sectors, can certainly be attributed to population growth driving increased demands for products and services, climate change, or improper urbanization. However, inadequate resource management in terms of neglecting the interlinkages between EWF resources is also a contributor. For example, improper resource use and inefficiency are mainly responsible for the current food insecurity challenges. Analysis of this issue reveals the fact that during the period 1950–1970, the urban population grew very rapidly, with a six-fold increase in global trade and water use (Hettiarachchi and Ardakanian, 2016; WTO, 2008).

LCA is recognized as a methodology that can evaluate the

**Table 6**
Nexus research development and implementation practice in different regions.

| Region | Nexus type | Reference | Main findings/results |
|---|---|---|---|
| South Asia | EWF | (Manthrithilake and Liyanagama, 2012) | Application of simulation model in water allocation policy resulting food and energy security for millions of people. |
| | EWF | (Rasul, 2014) | Explored regional food, water, and energy nexus emphasizing Hindu Kush Himalayan (HKH) ecosystem with the insurance of EWF security in downstream region and suggested integration between upstream and downstream areas for food, water, and energy security. |
| | EWF | (Gain et al., 2015) | Reviewed the EWF nexus literature along with prospects of nexus implementation in Bangladesh. The research results pointed that still there is a lack in the EWF nexus adaptation in the sector of policy documentation. |
| | EWF | (Kumar and Meena, 2017) | The mapping document showed that from 2007 there is a clear growth in nexus research in India and most of the nexus research are based on agriculture and irrigation. |
| Africa | EWF | (CGIAR, 2017) | Qualitatively and quantitatively assessed alternative water, energy, and food management, technology and governance opportunities resulting improvement in resource use efficiency for the underprivileged countryside people |
| | EWF | (Gulati et al., 2013) | Interrogation of interconnectedness among energy, water, food systems emphasizing the sustainable food production with strategic planning for resource conservation |
| | EWF | (Conway et al., 2015) | Main highlights are key regional institutional and policy structures in southern Africa. Climate change (particularly extreme events) along with socio-economic development pathways will exaggerate the inter-relationships in EWF nexus |
| | WE | (Mabhaudhi et al., 2016) | Recommended regional water and energy policy based on the water–energy nexus approach and pointed the lacking in water–energy nexus planning in Southern African Development Community (SADC) |
| | WE | (World Bank, 2016) | Assimilation of background data for supporting interdependency between the supply of electricity and water in Southern Africa and initiating energy-water nexus dialogue in the region |
| Europe & Central Asia | EWF | (Granit et al., 2012) | Investigation of Central Asian EWF nexus to find solutions of regional problems suggesting regional integrative nexus approach. |
| | EWF | (EastWest Institute, 2014) | Several EWF nexus limitations are addressed mentioning unsatisfactory regional participation between upstream and downstream countries. |
| | EWF | (Keskinen and Varis, 2016) | Discussed the applicability of nexus approach in different regions and rivers basins in Asia clearly focusing the water-centered concept. |
| | EWF | (UNESCAP, 2013) | Investigated the synergies and arguments on the water, food and energy (WFE) security nexus and pointed that Water-energy nexus and water-food nexus research are getting more emphasis rather than WFE nexus in this region. |
| | EWF | (Mayor et al., 2015) | This European Commission technical report pointed the opportunities for setting a resilient economy comprised of low carbon emission. |
| Latin America and the Caribbean | EWF | (Bellfield et al., 2015) | Focused Latin American countries in this report are: Bolivia, Brazil, Chile, Colombia, Ecuador, Mexico, and Peru. Targeted audience were public and private sector decision-makers in this region with an idea to provide information regarding key trade-offs between EWF and strategic planning to mitigate with a goal to start a regional nexus dialogue. |
| Middle East & North Africa | EWF | (Al-Ansari et al., 2014, 2015, 2016, 2017) | Developed an integrated EWF Nexus tool for the analysis of hypothetical food security question for the State of Qatar. The EWF Nexus tool adopts an LCA methodology and consists of representative EWF sub-systems and integrates them in one resource model. The modularity of the tool enables multiple technology configurations for given scenarios to be evaluated. The main findings of the study identified the sources of the largest contributors to global warming potential i.e. non energy related emissions from the food sectors in the form of enteric fermentation. Furthermore, the study identified a technology configuration for which the GWP can be reduced by approximately 98%. |
| | EWF | (UNESCWA, 2016) | Main goal is to construct analytical framework to examine the EWF nexus for Arab region. This report suggested people-centered nexus approach to make sure universal access to EWF for each person considering all EWF production and consumption system in the Arab region |
| | WE | (Siddiqi and Anadon, 2011) | Quantitative assessment of WE nexus in MENA region. Five sub regional grouping based on geographical adjacency and river basin: (1) Algeria, Libya, Morocco, and Tunisia; (2) Egypt; (3) Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, UAE, and Yemen; (4) Israel, Jordan, Lebanon, Palestine, and Syria (5) Iraq, Iran and Turkey. Results revealed energy sector has relatively weak dependency on fresh water while water abstraction and production systems is strongly dependent on energy. |
| | EWF | (Daher and Mohtar, 2015) | Presented a new EWF Nexus modeling tool (EWF Nexus Tool 2.0) capable of evaluating scenarios that helps to select best EWF resource allocation for the targeted audience (policy makers & researchers). In this paper, the tool was used for a case study bases on Qatar |
| East Asia & Pacific | WE | (Kenway and Lam, 2016) | 3 case studies based on Australia provided best monetary solutions along with water-energy efficiency and highlighted the lack in framework development which can examine the influence of energy sector on (direct & indirect) urban water systems. |
| | WE | (Kenway et al., 2008) | This report presented the energy dependency and associated greenhouse gas emission of 10 water facilities (water supply & wastewater treatment) located on Australia and New Zealand. |
| | WE | (Wang et al., 2012) | GHG emissions from groundwater pumping for irrigation in China was estimated using survey data from 11 provinces and briefly recommended policy implications. |
| | WE | (Feng et al., 2014) | This paper integrated process based LCA with input-output analysis for 8 electricity generation technologies in China to calculate their total life-cycle $CO_2$ emissions and water consumption. They demonstrated that 79% $CO_2$ reduction and 50% water savings are possible by a shift in energy mix, from current technology to renewables. |
| | WE | (Qin et al., 2015) | Water dependency for the energy sector was highlighted and concluded that the amount of water required for energy production is exclusively dependent on selection of technology. |

environmental performance of systems. It can be coupled with the EWF nexus in order to translate sub-system outputs from the different EWF representative processes into environmental scores (Al-Ansari et al., 2015). Consideration of the trade-offs and all environmental impacts of the total product system within the nexus sphere of study are enormously significant to policy makers, especially with respect to the allocation of resources between the different sectors. However, owing to the difficulties with data

collection, data accuracy, uncertainty in LCA results, and missing impact indicators, there is still a limited number of studies in which LCA is considered in EWF nexus evaluation.

LCA serves as an objective tool for assessing environmental impacts related to all life cycle stages for any product or process system. According to the ISO 14040:2006 standard, LCA is defined as the "compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006). The framework for LCA mainly consists of four stages, as shown in Fig. 5.

The life cycle inventory (LCI) phase involves the compilation of inputs and outputs over the entire lifetime of a definite product or process, whereas the aim of the life cycle impact assessment (LCIA) phase is to evaluate the potential environmental impacts throughout the life cycle. In the interpretation phase, the findings are evaluated to develop a conclusion. The combination of individual energy, water, and food systems forms the EWF nexus in which each system is represented by unit processes. LCA involvement in EWF nexus analysis enables quantification of material flows, in addition to resource and energy consumption for every single unit process, which in turn depicts the true environmental impacts. The total score of all unit processes indicates the performance of the total nexus system within the natural environment in which it operates (Al-Ansari et al., 2015). Several researchers have concentrated on this topic (Table 8) to identify the improvement opportunities in the EWF nexus area and to build a more sustainable environment (Al-Ansari et al., 2015; Dale and Bilec, 2014; Jeswani et al., 2015; Nair et al., 2014).

Considering a comprehensive review of EWF Nexus studies, it can be deduced that several studies that focused on energy utilization and food production involved the application of the LCA methodology. Although the aforementioned studies involved water analysis, the focus on this resource was less apparent. Evidently, the extent to which a particular resource presented itself as the focus of the study is dependent on the spatial characteristics of the study in question. Foodstuff with less possible environmental impact was highlighted by Jeswani et al. (2015). Issues related to the food-energy-water nexus were determined in the paper by applying LCA tools.

They analyzed the carbon, water, and energy footprints of world's known cereal product from Kellogg Europe. Using the LCA methodology, the environmental impact of the system in question, which included the production and packaging stages of the life-cycle, resulted in an average global warming potential (GWP) of 2.64 kg $CO_2$ eq./kg of cereal. It was deduced that the ingredients used in the final product were found to be the main contributor to GWP, accounting for 48% of which rice alone contributed 38%. The manufacturing stage was the main consumer of primary energy (34%), whereas 90% of the water footprint corresponded to the cultivation of ingredients. Considering other LCA impact categories, e.g., abiotic depletion potential (ADP), human toxicity potential (HTP), and land use, the production of ingredients was the key contributor. The consumption stage was also investigated, and modification in agricultural practices has been suggested to reduce the overall impacts, as rice is the ingredient that represents the main challenge for Kellogg cereal.

Considering each EWF nexus resource as a subsystem, Al-Ansari et al. (2015) presented an integrated energy, water, and food LCA tool to evaluate the environmental performance of a hypothetical food production scenario for the State of Qatar (Al-Ansari et al., 2015). The EWF nexus model developed consists of a series of sub-system LCI models representative of water, energy, and food resource sectors that were developed using material flow analysis and energy balances to quantify material flows, natural resources, and energy consumption at a component unit process level. The modular structure of the LCI database enables the practitioner to choose component unit processes so that different technological options can be considered (Al-Ansari et al., 2015). For the food

**Table 7**
Collation of EWF nexus tools (Chang et al., 2016; Flammini et al., 2014).

| Tool | Nexus elements | Type | Author/ Institution | Environmental consideration in output | Features |
|---|---|---|---|---|---|
| Nexus 1.0 and 2.0 Tool | E-W-F | IO | QEERI | Local $CO_2$ emission | Scenario based computational tool that portrays different states by varying food self-sufficiency, water source, energy source and importing country |
| WEAP (Water Evaluation and Planning) | E-F | IO | SEI | GHG emissions | Unique integrated approach capable to conduct assessment of water resource planning |
| LEAP (Long-range Energy Alternatives Planning System) | | | | | Considered as versatile user-friendly software aimed to analysis energy policy and GHG reduction planning |
| MuSIASEM (Multi Scale Integrated Analysis of Societal and Ecosystem Metabolism) | W-E-F | Flow-fund | IASTE | Ecological impacts | Effectively examines the interrelationship between EWF with the consideration of heterogeneous factors |
| CLEWS (Climate, Land, Energy and Water Strategies) | C-L-W-E | Scenario based | KTH & UNDSD | GHG emission | Integrated systems approach aiming to investigate the interactions between different connected sectors |
| Sankey Diagram | E-W-F | Flow diagram | N/A | N/A | Presents the water, energy, and food flows in each stage with the help of visual mapping. This tool has been applied in Australia (household level), Beijing, China (regional) and USA. |
| REAP (Resources and Energy Analysis Programme) | F-E | MD | SEI | GHG emission and Ecological footprint | Explores the negative environmental impacts due to the change in energy production system over time |
| WBCSD Water, Energy, Food/Feed/ Fiber/Fuel Nexus Tool | E-W-F | IR | WBCSD | N/A | Measures the interconnectedness between EWF resources. |

IASTE = Integrated Assessment: Sociology, Technology and the Environment.
SEI = Stockholm Environment Institute.
WBCSD = World Business Council for Sustainable Development.
QEERI = Qatar Environment and Energy Research Institute.
KTH = Royal Institute of Technology, Sweden.
UNDSD = United Nations Division for Sustainable Development.
IR = Information Resources (e.g. maps).
MD = Modeling Tools.
N/A = Not Available.

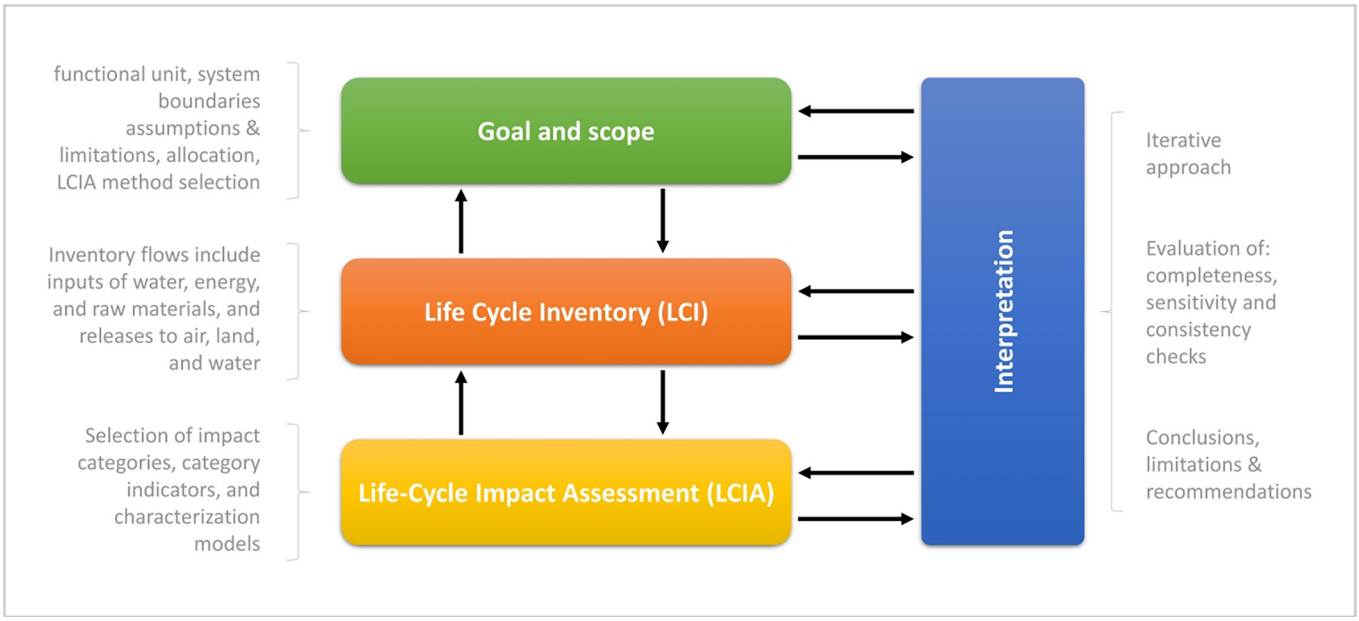
functional unit, system boundaries assumptions & limitations, allocation, LCIA method selection
Goal and scope
Inventory flows include inputs of water, energy, and raw materials, and releases to air, land, and water
Life Cycle Inventory (LCI)
Selection of impact categories, category indicators, and characterization models
Life-Cycle Impact Assessment (LCIA)
Interpretation
Iterative approach
Evaluation of: completeness, sensitivity and consistency checks
Conclusions, limitations & recommendations

**Fig. 5.** The Life Cycle Assessment framework based on ISO 14040.

production system in question that involved raising domestic food production by 40% to meet a perceived self-sufficiency level for the State of Qatar, multiple technology configurations were evaluated. In all scenarios, emissions from enteric fermentation from livestock were responsible for the largest contribution towards GWP. The total GWP is reduced through the integration of technology and through the re-configuration of the sub-systems. The full integration of photovoltaics, biomass gasification and carbon capture integrated with biomass integrated combined cycle demonstrated in Al-Ansari et al. (2016, 2017) achieved a near carbon neutral EWF nexus system in the development of the domestic food production system (Al-Ansari et al., 2016, 2017).

Attaining food security while maintaining the biodiversity and integrity of ecosystems with changes in the consumption pattern is discussed by De Laurentiis et al. (2016). They considered several peer-reviewed articles related to LCA and food systems within the nexus and identified five different applications of LCA: deployment of sustainable production methods, changes in dietary trends, comparison of meal choice, food waste reduction, and the role of packaging. Energy footprint and GHG emission from irrigation and interstate food transfer were analyzed for the production and trading of 29 food commodities between 51 states in USA (Vora et al., 2017). Network analysis highlighted the impacts of irrigation and compared it to another high GHG intensive cement industry. Animal based food was found to have relatively high GHG emission indicating the need of change in the food consumption pattern. A few states such as NC, ND and UT were considered as top exporters of virtual water releasing high GHG, thus highlighting the importance of low-pressure irrigation techniques, reduction in irrigation water loss and other factors.

Focusing on the environmental impacts of extracting Marcellus Shale natural gas, a model was developed using LCA to discuss future energy and water pathways in Pennsylvania, Brazil, and Arizona (Dale and Bilec, 2014). Projected electricity demand indicates that it will be difficult for Brazil to meet carbon targets, as GHG emission intensity will increase 47% by 2020 and reach 82% by 2040. Alternative energy sources, such as solar and wind, have been suggested as potential alternatives, which can reduce the intensity of GHG emissions. The biggest challenge for Pennsylvania's water-energy nexus may present itself in the form of competing interests between its biofuel production and shale gas drilling activities. In the case of Arizona, environmental impacts are mitigated within the water-energy nexus by adopting efficiency measures to promote resource conservation and through reduction in population growth (Dale and Bilec, 2014).

Application of LCA in biogas production from three different crops in three different areas demonstrated that the cultivation phase is the highest contributor to water resource depletion. Incidentally, southern Italy was deemed unsustainable for bioenergy production from the water management viewpoint (Pacetti et al., 2015). For a nexus case study in China involving energy sector water withdrawal, consumption and wastewater withdrawal, it was deduced that the environmental impacts due to life cycle water use for energy production are more severe in the north and northwest parts of China based on LCA (Zhang and Anadon, 2013). Similarly, water use for energy production was highlighted with an LCA tool to evaluate methods for more sustainable water reduction with the ultimate reduction in life cycle $CO_2$ (Feng et al., 2014).

Water supply scenarios were evaluated using life-cycle approaches for two different locations in the USA (Tampa Bay and San Diego), where they found lower GHG emissions and energy cost in San Diego than Tampa Bay for most of the water infrastructure due to the difference in electricity grid mix and the characteristics of water resources (Mo et al., 2014). LCA was successfully employed in a groundwater pumping system in a study in Kairouan, Tunisia to ascertain the associated environmental impacts caused by different pumping systems. The impact contribution in different stages of groundwater pumping was also determined by utilizing LCA (Pradeleix et al., 2015). Energy usage in an energy-intensive pumping system is the highest contributor to the human health, resource depletion, and ecosystem impact categories.

Evidently, from the review of studies involving the nexus of two or more resources, a hybrid LCA - nexus approach towards integrated resource modeling can provide insight into environmental loads from systems that utilize EWF resources. Whilst a nexus approach emphasizes the need to consider the interlinkages between resources, an LCA application will consider the environmental loads for the sub-systems that constitute the resource sectors.

**Table 8**
Water, Energy and Food nexus research involving Life Cycle Assessment.

| Study | Focus point | Tool/Model | LCIA | Highlights/main findings | Targeted audience |
|---|---|---|---|---|---|
| (Al-Ansari et al., 2015) | Food production system | EWF nexus Tool | CML 2001 | Largest contributor of GWP is non- energy emissions from food sector. utilization of solar energy, can be potential solution to reduce 30% GWP | Strategic energy, water and food policy makers |
| (Jeswani et al., 2015) | Complete food supply chain | GaBi V6.4 | CML 2001 | Production stage of raw ingredients is responsible for main GWP and 90% water consumption while manufacturing stage is the highest user of primary energy. | Kellogg and other food companies |
| (De Laurentiis et al., 2016) | Food production & consumption pattern | N/A | N/A | Potential of applying LCA in shifting both food production and consumption pattern | Food service providers |
| (Vora et al., 2017) | Interstate food trade | NA | IPCC & Cumulative Energy Demand (CED) | Results showed that embodied GHG emission associated with irrigation practice is similar to GHG emission from cement manufacturing in USA and interstate food transfer has higher embodied energy and GHG emission. | 51 States of the United States of America |
| (Dale and Bilec, 2014) | Regional energy and water supply scenarios | N/A | IPCC & Cumulative Energy Demand (CED) method version 1.06 | Confirmation of equal GHG emission from shale gas and conventional gas resulted by life cycle assessment | Selected US regions: Arizona, Pennsylvania, or Brazil |
| (Berger and Finkbeiner, 2010) | Review of impact assessment for water use | N/A | N/A | Wide range of impact assessment methods for water use has been presented with methodological advantages and shortcomings | N/A |
| (Zhang and Anadon, 2013) | Water use in energy production and related environmental impacts | Multi-regional input-output model | Eco-indicator 99 | Energy generation using coal dominates in China and environmental impacts due to the water use in energy production highly influenced by uneven distribution of geographical water | Policy makers in water resources management |
| (Feng et al., 2014) | Total life-cycle carbon emission and water consumption for different electricity generation scenarios | Hybrid LCA | N/A | Study results showed that use of renewables such as wind power can reduce 79% $CO_2$ emission with 83% less water consumption while use of PV and nuclear for power generation has the potential to reduce $CO_2$ emission but lacks the ability to reduce water use as wind power. | Water scarce provinces in China |
| (Pacetti et al., 2015) | Production of bio-gas (anaerobic digestion method) | SimaPro 7 | ReCiPe 2008 | LCA results showed that there are negative impacts in production of bio-gas due to the fertilizer use and irrigation process. | Northern, central and southern Italy |
| (Mo et al., 2014) | Evaluated the impact of current and future water supply scenarios | IO based hybrid LCA | N/A | Due to the difference in electricity production and water resource, San Diego was found to emit overall more GHG than Tampa Bay in most scenarios. | Tampa Bay, Florida & San Diego, California |
| (Pradeleix et al., 2015) | Aims to assess the environmental impacts of groundwater pumping | SimaPro 7.3 | ReCiPe 2008 | Most environmental impacts in groundwater pumping system is for energy use in pumping, causing resource depletion, human health toxicity and ecosystem impacts. | Semi-arid central Tunisia |

## 5. Conclusion and outlook

The world is facing extreme challenges with respect to energy, water and food resources, from both supply and demand perspectives. However, all these energy, water, and food systems depend heavily on each other and contribute significantly to several environmental impacts such as GHG emission, resource depletion, and eutrophication, among others. Therefore, coupled with a need to limit environmental degradation, it is crucial that EWF resource utilization is optimized to minimize impacts on the environment, and to do so within an economically viable framework. The comprehensive review presented in this paper provided a descriptive analysis of the interdependencies between energy, water, and food resource sectors. The review highlights the nature of these interlinkages that vary among nations due to the uneven distribution of global resources. For instance, analysis on the regional progress in EWF nexus studies revealed the fact that most studies in the East Asia and Pacific region are concerned on analyzing the energy and water nexus system.

This paper has also detailed the application of different nexus tools to examine and quantify environmental loads associated with the EWF nexus system. The output of the analysis of different nexus tools shows that, other than the LCA tool, most of them are limited to quantifying environmental impacts such as GHG or $CO_2$ emissions only. The application of the LCA methodology provides a means for which environmental quantification can be achieved for a range of environmental loads and for all processes within the nexus throughout their lifecycle. Impact analysis for a range of environmental loads enables us to justify the EWF nexus from different perspectives such as human health, ecosystem quality, resource conservation, and climate change, among others. Furthermore, as the EWF nexus analysis can involve multiple scenarios, the LCA methodology is conducive to such analysis, enabling the comparison of the different options and the identification of the optimum solution. Thus, it provides a baseline against which policy makers can set their target identifying the critical areas that form different angles in the specific EWF nexus system.

A major hindrance to the application of LCA based approach is the need for region specific LCI databases to enable robust analysis. Thus, a major future work is required in the development of such databases related particularly to energy, water and food related process inputs and activities. As far as the LCA methods are concerned, studies combining both the EWF nexus and LCA followed different LCA methodologies to characterize the environmental impact categories, in which direct comparison between the values from different methods is not practical. Similarly, the difference in

study objectives, system boundaries, and applied databases increases the difficulty in applying the study results to real policy formulations for EWF nexus systems.

Presenting a major area for future work and global databases for the life-cycle analysis of every EWF system will allow all the existing nexus systems to verify their environmental acceptability as well as the future EWF systems to act in a more environmentally friendly way. Integration of consumption patterns as well as consumers behavior in nexus study can play a significant role in reducing the overall environmental impact in the future.

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## References

Al-Mutawa, A.M., Al Murbati, W.M., Al Ruwaili, N.A., Al Oraifi, A.S., Al Oraif, A., Al Arafati, A., Nasrullah, A., Al Bahow, Md R., Al Anzi, Saad Mohsin, Rashidi, Md, Al Moosa, Saud Zaid, 2014. In: Desalination in the GCC : The History, the Present & the Future.

Abderrahman, W.A., 2001. Energy and water in Arid developing countries: Saudi Arabia, a case-study. Water Resources Development 17 (2), 247–255.

Al-Ansari, T., Korre, A., Nie, Z., Shah, N., 2014. Development of a life cycle methodology for the energy, water and food nexus. In: The 24th European Symposium on Computer Aided Process Engineering: Escape. Hungary.

Al-Ansari, T., Korre, A., Nie, Z., Shah, N., 2015. Development of a life cycle assessment tool for the assessment of food production systems within the energy, water and food nexus. Sustainable Production and Consumption 2, 52–66.

Al-Ansari, T., Korre, A., Nie, Z., Shah, N., 2016. Integration of biomass gasification and CO2 capture in the LCA model for the energy, water and food nexus. In: The 26th European Symposium on Computer Aided Process Engineering: Escape Slovenia.

Al-Ansari, T., Korre, A., Nie, Z., Shah, N., 2017. Integration of greenhouse gas control technologies within the energy, water and food nexus to enhance the environmental performance of food production systems. J. Clean. Prod. 162 (Suppl. C), 1592–1606.

Al-Ghamdi, S.G., Bilec, M.M., 2015. Life-cycle thinking and the LEED rating system: global perspective on building energy use and environmental impacts. Environmental Science & Technology 49 (7), 4048–4056.

Allan, J.A., 2003. Virtual water - the water, food, and trade nexus. Useful concept or Misleading Metaphor? Water Int. 28 (1), 106–113.

Apostolidis, N., 2010. Australian experience in water and energy footprints. Water Pract. Technol. 5 (4), wpt2010076.

Atlantic Council, 2011. Energy for Water and Water for Energy: a Report on the Atlantic Council's Workshop How the Nexus Impacts Electric Power Production in the United States.

Bellfield, H., Deutsche Gesellschaft für Internationale Zusammenarbeit, Wasser, E.u.T., Climate, Development Knowledge Network, c., International Water, A, 2015. Water Energy and Food Nexus in Latin America and the Caribbean.

Berger, M., Finkbeiner, M., 2010. Water footprinting: how to address water use in life cycle assessment? Sustainability 2 (4), 919–944.

Scanlon, Bridget R., Duncan, Ian, Reedy, Robert C., 2013. Drought and the water–energy nexus in Texas. Environmental Research Letters 8.

Carol Maas, 2010. Ontario's Water-energy Nexus: Will We Find Ourselves in Hot Water… or Tap into Opportunity?.

CGIAR, 2017. The water-energy-food nexus: global, basin and local case studies of resource use efficiency under growing natural resource scarcity. In: Research Program on Water, Land and Ecosystems.

Chang, Y., Li, G., Yao, Y., Zhang, L., Yu, C., 2016. Quantifying the water-energy-food nexus: current Status and trends. Energies 9 (2), 1–17.

Conway, D., van Garderen, E.A., Deryng, D., Dorling, S., Krueger, T., Landman, W., Lankford, B., Lebek, K., Osborn, T., Ringler, C., Thurlow, J., Zhu, T., Dalin, C., 2015. Climate and southern Africa's water-energy-food nexus. Nat. Clim. Change 5 (9), 837–846.

Copeland, C., Carter, N.T., 2017. In: Service, C.R. (Ed.), Energy-water Nexus: the Water Sector's Energy Use.

Daher, B.T., Mohtar, R.H., 2015. Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. Water Int. 40 (5–6), 748–771.

Dale, A.T., Bilec, M.M., 2014. The regional energy & water supply scenarios (REWSS) model, part II: case studies in Pennsylvania and Arizona. Sustainable Energy Technologies and Assessments 7 (Suppl. C), 237–246.

Darwish, M., 2014. Qatar water problem and solar desalination. Desalination and Water Treatment 52 (7–9), 1250–1262.

Darwish, M.A., Rabi, M., 2012. Qatar water challenges. Desalination and Water Treatment 51 (1–3), 75–86.

De Laurentiis, V., Hunt, D.V.L., Rogers, C.D.F., 2016. Overcoming food security challenges within an energy/water/food nexus (EWFN) approach. Sustainability 8 (1), 1–23.

DOE, 2006. Energy Demands on Water Resources: Report to Congress on the Interdependency of Energy and Water. US Department of Energy.

EastWest Institute, 2014. Triggering Cooperation across the Food-water-energy Nexus in Central Asia.

EEA, 2008. Water use by sectors (IND-11-en). European Environment Agency.

Endo, A., Tsurita, I., Burnett, K., Orencio, P.M., 2017. A review of the current state of research on the water, energy, and food nexus. J. Hydrol.: Reg. Stud. 11, 20–30.

EPA, 2013. Strategies for Saving Energy at Public Water Systems (EPA 816-F-13-004). United States Environmental Protection Agency.

FAO, 2012. Energy-smart Food at FAO: an Overview, at a Glance: the Role of Energy in Food Security and Climate. Food and Agriculture Organization of the United Nations.

FAO, 2014. The Water-energy-food Nexus: a New Approach in Support of Food Security and Sustainable Agriculture. Food and Agriculture Organization of the United Nations.

Feng, K., Hubacek, K., Siu, Y.L., Li, X., 2014. The energy and water nexus in Chinese electricity production: a hybrid life cycle analysis. Renew. Sustain. Energy Rev. 39, 342–355.

Finley, J.W., Seiber, J.N., 2014. The nexus of food, energy, and water. J. Agric. Food Chem. 62 (27), 6255–6262.

Flammini, A., Puri, M., Pluschke, L., Dubois, O., 2014. Food, agriculture organization of the united, N., climate, E., tenure, D.. In: Walking the Nexus Talk : Assessing the Water-energy-food Nexus in the Context of the Sustainable Energy for All Initiative.

Foundation on Future Farming, 2008. Agriculture at a Crossroads: IAASTD Findings and Recommendations for Future Farming.

Frenken, K., Gillet, V., 2012. Irrigation Water Requirement and Water Withdrawal by Country (FAO AQUASTAT Reports).

Friedrich, E., 2002. Life-cycle assessment as an environmental management tool in the production of potable water. Water Sci. Technol. 46 (9), 29–36.

Gain, A.K., Giupponi, C., Benson, D., 2015. The water–energy–food (WEF) security nexus: the policy perspective of Bangladesh. Water Int. 40 (5–6), 895–910.

Granit, J., Jägerskog, A., Lindström, A., Björklund, G., Bullock, A., Löfgren, R., de Gooijer, G., Pettigrew, S., 2012. Regional options for addressing the water, energy and food nexus in central Asia and the aral Sea basin. Int. J. Water Resour. Dev. 28 (3), 419–432.

Guan, D., Hubacek, K., 2008. A new and integrated hydro-economic accounting and analytical framework for water resources: a case study for North China. J. Environ. Manag. 88 (4), 1300–1313.

Gulati, M., Jacobs, I., Jooste, A., Naidoo, D., Fakir, S., 2013. The water–energy–food security nexus: challenges and opportunities for food security in South Africa. Aquatic Procedia 1, 150–164.

Hardy, L., Garrido, A., Juana, L., 2012. Evaluation of Spain's water-energy nexus. Int. J. Water Resour. Dev. 28 (1), 151–170.

Hellegers, P., Zilberman, D., Steduto, P., McCornick, P., 2008. Interactions between water, energy, food and environment: evolving perspectives and policy issues. Water Pol. 10 (S1), 1–10.

Hettiarachchi, H., Ardakanian, R., 2016. Environmental Resource Management and the Nexus Approach. SpringerLink, Switzerland.

Hightower, M., Pierce, S.A., 2008. The energy challange. Nature 452 (7185), 285–286.

Hoff, H., 2011. Understanding the Nexus. Background Paper for the Bonn2011 Conference:The Water, Energy and Food Security Nexus – Solutions for a Green Economy. Stockholm Environment Institute, Stockholm.

Hu, G., Ou, X., Zhang, Q., Karplus, V.J., 2013. Analysis on energy–water nexus by Sankey diagram: the case of Beijing. Desalination and Water Treatment 51 (19–21), 4183–4193.

ICF Consulting, 2002. Water & Sustainability (Volume 4): U.S. Electricity Consumption for Water Supply & Treatment—the Next Half Century (Topical Report 1006787). Electric Power Research Institute (EPRI), Palo Alto, CA.

ICF International, 2008. Water and Energy: Leveraging Voluntary Programs to Save Both Water and Energy. National Service Center for Environmental Publications, Washington, DC.

IEA, 2012. Water for Energy: Is Energy Becoming a Thirstier Resouces? International Energy Agency.

ISO, 2006 ISO 14040, 2006. Environmental Management - Life Cycle Assessment - Principles and Framework (en). https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en.

Jackson, T.M., Khan, S., Hafeez, M., 2010. A comparative analysis of water application and energy consumption at the irrigated field level. Agric. Water Manag. 97 (10), 1477–1485.

Jeswani, H.K., Burkinshaw, R., Azapagic, A., 2015. Environmental sustainability issues in the food–energy–water nexus: Breakfast cereals and snacks. Sustainable Production and Consumption 2, 17–28.

Kahrl, F., Li, Y., Su, Y., Tennigkeit, T., Wilkes, A., Xu, J., 2010. Greenhouse gas emissions from nitrogen fertilizer use in China. Environ. Sci. Pol. 13 (8), 688–694.

Kahrl, F., Roland-Holst, D., 2007. China's water–energy nexus. Water Pol. 10 (S1), 51–65.

Kenway, S.J., Lam, K.L., 2016. Quantifying and managing urban water-related energy

use systemically: case study lessons from Australia. Int. J. Water Resour. Dev. 32 (3), 379–397.
Kenway, S.J., Priestley, A., Cook, S., Seo, S., Inman, M., Gregory, A., Hall, M., 2008. Energy Use in the Provision and Consumption of Urban Water in Australia and New Zealand. Water Services Association of Australia.
Keskinen, M., Varis, O., 2016. Water-energy-food nexus in large Asian river Basins. Water 8 (10), 446.
Klein, G., 2005. California's Water – Energy Relationship (CEC-700-2005-011-sf). California Energy Comission. Final Staff Report.
Kumar, S., Meena, M.L., 2017. Water-energy-food nexus research in India. Int. J. Appl. Environ. Sci. 12 (2), 265–273.
Lenntech, B.V., 2017. Use of Water in Food and Agriculture. https://www.lenntech.com/water-food-agriculture.
Lillie, K., 2015. Energy Use in Food Production. https://www.chooseenergy.com/blog/energy-101/energy-food-production/.
Maas, C., 2009. Greenhouse Gas and Energy Co-benefits of Water Conservation. POLIS Research Report 09–01.
Mabhaudhi, T., Mpandeli, S., Madhlopa, A., Modi, A., Backeberg, G., Nhamo, L., 2016. Southern Africa's water–energy nexus: towards regional integration and development. Water 8 (6), 235.
Macknick, J., Newmark, R., Heath, G., Hallett, K.C., 2011. A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies (NREL/TP-6A20-50900). U.S. Department of Energy.
Maharjan, I., 2015. Energy Efficiency in Water and Wastewater Treatment Facilities: Leveraging Measurement and Verification (M&V) and Funding Program. Ontario Clean Water Agency.
Manthrithilake, H., Liyanagama, B.S., 2012. Simulation model for participatory decision making: water allocation policy implementation in Sri Lanka. Water Int. 37 (4), 478–491.
Marsh, D.M., 2008. The Water-energy Nexus : a Comprehensive Analysis in the Context of New South Wales (Doctoral Dissertation). Faculty of Engineering and Information Technology University of Technology, Sydney.
Mayor, B., lopez-gunn, E., Hernaez, O., Zugasti, I., 2015. The Water-energy-food Nexus: Foresight for Research and Innovation in the Context of Climate Change (European Commission report).
Meda, A., Lensch, D., Schaum, C., Cornel, P., 2012. Energy and Water: Relations and Recovery Potential. IWA Publishing, London, UK.
Mekonnen, M.M., Hoekstra, A.Y., 2010. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15 (5), 1577–1600.
Mekonnen, M.M., Hoekstra, A.Y., 2012. A global assessment of the water footprint of farm animal products. Ecosystems 15 (3), 401–415.
Mielke, E., Anadon, L.D., Narayanamurti, V., 2010. Water Consumption of Energy Resource Extraction, Processing, and Conversion (Discussion Paper: 2010-15). Harvard Kennedy School Belfer Center.
Miller, L.A., Ramaswami, A., Ranjan, R., 2013. Contribution of water and wastewater infrastructures to urban energy Metabolism and greenhouse gas emissions in cities in India. J. Environ. Eng. 139 (5), 738–745.
Mo, W., Wang, R., Zimmerman, J.B., 2014. Energy–water nexus analysis of enhanced water supply scenarios: a regional comparison of Tampa Bay, Florida, and san Diego, California. Environmental Science & Technology 48 (10), 5883–5891.
Mohammed, S., Darwish, M.A., 2016. Water footprint and virtual water trade in Qatar. Desalination and Water Treatment 66, 117–132.
Nabil Dabour, 2006. Water resources and their use in agriculture in Arab countries. Journal of Economic Cooperation 27 (1), 1–38.
Nair, M., Kumar, D., 2013. Water desalination and challenges: the Middle East perspective: a review. Desalination and Water Treatment 51 (10–12), 2030–2040.
Nair, S., George, B., Malano, H.M., Arora, M., Nawarathna, B., 2014. Water–energy–greenhouse gas nexus of urban water systems: review of concepts, state-of-art and methods. Resources. Conserv. Recycl. 89, 1–10.
National Research Council, 2008. Desalination: a National Perspective. The National Academies Press, Washington, DC.
Ozturk, I., 2015. Sustainability in the food-energy-water nexus: evidence from BRICS (Brazil, the Russian Federation, India, China, and South Africa) countries. Energy 93, 999–1010.
Ozturk, I., 2017. The dynamic relationship between agricultural sustainability and food-energy-water poverty in a panel of selected Sub-Saharan African Countries. Energy Pol. 107, 289–299.
Pacetti, T., Lombardi, L., Federici, G., 2015. Water–energy Nexus: a case of biogas production from energy crops evaluated by Water Footprint and Life Cycle Assessment (LCA) methods. J. Clean. Prod. 101, 278–291.
Passioura, J., 2006. Increasing crop productivity when water is scarce—from breeding to field management. Agric. Water Manag. 80 (1), 176–196.
Plappally, A.K., Lienhard V, J.H., 2012. Energy requirements for water production, treatment, end use, reclamation, and disposal. Renew. Sustain. Energy Rev. 16 (7), 4818–4848.
Pradeleix, L., Roux, P., Bouarfa, S., Jaouani, B., Lili-Chabaane, Z., Bellon-Maurel, V., 2015. Environmental impacts of contrasted groundwater pumping systems assessed by life cycle assessment methodology: contribution to the water–energy nexus study. Irrigat. Drain. 64 (1), 124–138.
Pretty, J.N., 1993. Food and energy: strategies for sustainable development by ignacy Sachs and dana Silk united nations university press, tokyo, 1990, 83. Food Pol. 18 (5), 453–454.
Qin, Y., Curmi, E., Kopec, G.M., Allwood, J.M., Richards, K.S., 2015. China's energy-water nexus – assessment of the energy sector's compliance with the "3 Red Lines" industrial water policy. Energy Pol. 82, 131–143.
Radcliffe, J.C., 2004. Water Recycling in Australia. Australian Academy of Technological Sciences and Engineering Parkville, Victoria.
Raluy, R.G., Serra, L., Uche, J., 2005a. Life cycle assessment of desalination technologies integrated with renewable energies. Desalination 183 (1), 81–93.
Raluy, R.G., Serra, L., Uche, J., Valero, A., 2005b. Life cycle assessment of water production technologies - Part 2: reverse osmosis desalination versus the ebro river water transfer (9 pp). Int. J. Life Cycle Assess. 10 (5), 346–354.
Rasul, G., 2014. Food, water, and energy security in South Asia: a nexus perspective from the Hindu Kush Himalayan region. Environ. Sci. Pol. 39, 35–48.
Rocheta, E., Peirson, W., 2011. Urban Water Supply in a Carbon Constrained Australia: Water-energy Linkages. National Climate Change Adaptation Research Facility.
Rothausen, S.G.S.A., Conway, D., 2011. Greenhouse-gas emissions from energy use in the water sector. Nat. Clim. Change 1 (4), 210–219.
Scott, C.A., 2011. The water-energy-climate nexus: resources and policy outlook for aquifers in Mexico. Water Resour. Res. 47 (6).
Shah, T., 2009. Climate change and groundwater: India's opportunities for mitigation and adaptation. Environ. Res. Lett. 4 (3).
Siddiqi, A., Anadon, L.D., 2011. The water–energy nexus in Middle East and North Africa. Energy Pol. 39 (8), 4529–4540.
Smith, K., Liu, S., Chang, T., 2016. Contribution of urban water supply to greenhouse gas emissions in China. J. Ind. Ecol. 20 (4), 792–802.
Sovacool, B.K., Sovacool, K.E., 2009. Identifying future electricity–water tradeoffs in the United States. Energy Pol. 37 (7), 2763–2773.
Tan, C., Zhi, Q., 2016. The energy-water nexus: a literature review of the dependence of energy on water. Energy Procedia 88, 277–284.
The World Bank, 2016. Regions: Annual Report 2016. http://www.worldbank.org/en/about/annual-report/regions.
UNESCAP, 2013. The Status of the Water, Food and Energy Nexus in Asia and the Pacific. United Nations Economic and Social Commission for Asia and Pasific.
UNESCO-IHE Institute for Water Education, 2008. Annual Report https://www.un-ihe.org/sites/default/files/annual_report_2008.pdf.
UNESCO, 2017. DESWARE Encyclopedia of Desalination and Water Resources. United Nations Educational Scientific and Cultural Organization.
UNESCWA, 2016. The Water, Energy and Food Security Nexus in the Arab Region. United Nations Economic and Social Commission for Western Asia.
Union of Concerned Scientists, 2017. How it Works: Water for Electricity. http://www.ucsusa.org/clean-energy/energy-water-use/water-energy-electricity-overview#.WVeDm2iGPIU.
Vora, N., Shah, A., Bilec, M.M., Khanna, V., 2017. Food–energy–water nexus: quantifying embodied energy and GHG emissions from irrigation through virtual water transfers in food trade. ACS Sustain. Chem. Eng. 5 (3), 2119–2128.
Wakeel, M., Chen, B., Hayat, T., Alsaedi, A., Ahmad, B., 2016. Energy consumption for water use cycles in different countries: a review. Appl. Energy 178, 868–885.
Wang, J., Rothausen, S., G. S. A, Conway, D., Zhang, L., Xiong, W., Holman, I.,P., Li, Y., 2012. China's water–energy nexus: greenhouse-gas emissions from groundwater use for agriculture. Environ. Res. Lett. 7 (1), 014035.
Webber, M.E., 2008. Energy versus Water: Solving Both Crises Together. https://www.scientificamerican.com/article/the-future-of-fuel/.
Wicaksono, A., Jeong, G., Kang, D., 2017. Water, energy, and food nexus: review of global implementation and simulation model development. Water Pol. 19 (3), 440–462.
Williams, A.G., Audsley, E., Sandars, D.L., 2006. Determining the Environmental Burdens and Resource Use in the Production of Agricultural and Horticultural Commodities. Defra project report IS0205.
Woods, J., Williams, A., Hughes, J.K., Black, M., Murphy, R., 2010. Energy and the food system. Phil. Trans. Biol. Sci. 365 (1554), 2991–3006.
World Bank, 2016. Southern Africa Energy-water Nexus :Background Paper to Support Dialogue in the Region. https://openknowledge.worldbank.org/handle/10986/24667.
World Energy Council, 2010. Water for Energy. https://www.worldenergy.org/wp-content/uploads/2012/10/PUB_Water_For_Energy_2010_WEC.pdf.
WTO, 2008. World Trade Report 2008. https://www.wto.org/english/res_e/booksp_e/anrep_e/world_trade_report08_e.pdf.
Xie, T., Chengwen, W., 2012. Energy consumption in wastewater treatment plants in China. In: World Congress on Water, Climate and Energy. Dublin, Ireland.
Zhang, C., Anadon, L.D., 2013. Life cycle water use of energy production and its environmental impacts in China. Environmental Science & Technology 47 (24), 14459–14467.